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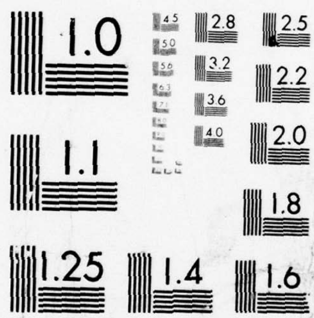

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An experimental investigation of the combustion behavior in solid fuel ramjets was conducted. Light extinction measurements were employed to determine the effects of fuel composition and bypass ratio on the combustion efficiency and the percent and size of unburned carbon. Utility and limitations of the optical method are presented.

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I. INTRODUCTION

A better understanding of the internal ballistics of the solid fuel ramjet is required if the concept is to become a viable tactical propulsive system. Past studies have shown the importance of parameters such as flame holder step size, aft combustor entrance step size, aft mixing chamber L/D and aft mixing techniques.

Recent work done by Mady and Netzer[1], to better understand the effects of bypass air on combustion efficiency, was conducted by varying bypass mass flow rates, dump momentum, number of dumps and angular orientation into the aft mixing chamber.

With bypass (low mass flux through the fuel port) and polymethylmethacrylate (PMM) fuel grains it was found that the regression rate did not vary with air mass flux. The regression rate for bypass configurations took the form:

$$\dot{r} = 0.0016\ P^{.42}\ G^{.003} \qquad (1)$$

where P = chamber pressure in psia and G = the air mass flux in $\mathrm{lbm/in^2\text{-}sec}$. It was suggested that in the bypass configuration (low G, high P and fuel rich within the fuel port) the principal mechanism for wall heat flux became radiation and thus the regression rate was insensitive to G.

For the non-bypass configuration with PMM fuel grains, port fuel-air ratios were generally lean and the regression rates took the form:

$$\dot{r} = 0.0043\ P^{.29}\ G^{.38} \qquad (2)$$

Performance computations showed a significant decrease in combustion efficiency for all bypass configurations which were used. It was concluded that the monomer/small polymer and/or carbon which entered the aft mixing

chamber would react most completely if allowed to mix slowly with the hot core gases. Bypass air apparently quenched these reactions within the thin reacting shear layer downstream of the fuel grain.

Work at the Naval Weapons Center, China Lake, and at the Chemical Systems Division, United Aircraft (CSD), have shown that when all-hydrocarbon fuel grains are used in the solid fuel ramjet, combustion efficiency could be improved with proper introduction of bypass air. These fuels characteristically have higher regression rates than PMM and much of the fuel probably leaves the fuel surface as larger polymers. Apparently the unburned hydrocarbons/carbon are hot enough and the fuel port flow rich enough that bypass air can increase the reaction rates within the aft mixing chamber.

Additional experimental work by Schadow[2] with all-hydrocarbon fuels, and modeling efforts by Netzer[3] have indicated that a considerable amount of unburned carbon and/or hydrocarbons are present at the aft end of the fuel grain. It has also been suggested that inefficiency of the combustion process is directly related to the unburned carbon. Modeling efforts at CSD[4] have also indicated that approximately 50% of the vaporized fuel escapes from under the flame within the fuel grain and enters the aft mixing chamber. Except for the gas sampling and temperature measurements made by Schadow, the above conclusions were based on theoretical predictions or indirect data (such as average combustion efficiency, fuel regression rate, etc). Direct evidence of the effects of bypass on combustion behavior remains to be obtained.

In recent years considerable advances have been made in the utilization of light extinction and light scattering methods[5,6] for the study of combustion behavior.

Cashdollar, Lee and Singer[7] have employed an optical transmissometer for measuring carbon particle size and concentration in a wood tunnel fire. Lester and Wittig[8] successfully utilized the light extinction method to find particle sizes and concentration during methane combustion in a shock tube. Powell, et. al.[9] utilized both the extinction and forward scattering of light measurement methods to study smoke particles in building fires. Although the latter method negates the requirement for a-priori knowledge of the refractive index of the particles, it is more difficult to adapt to practical combustion chamber geometries. Bernard and Penner[10] have also used scattered laser power spectra to determine particle sizes in flames.

This investigation was concerned with further study of the combustion process within solid fuel ramjets. Unburned carbon sizes and concentrations were determined in the aft mixing chamber, both at the fuel grain exit and just prior to the exhaust nozzle. An optical technique was employed which involved the light extinction method of measuring average particle diameters in an aerosol[5,6,7].

II. METHOD OF INVESTIGATION

Experimental firings of a solid fuel ramjet were conducted using both PMM and all-hydrocarbon fuel grains. The tests were performed to further investigate the effects of bypass airflow by varying primary to bypass air flow ratios. A schematic of the test apparatus is shown in Fig. 1.

An in situ optical technique was utilized to measure average size and concentration of carbon particulates generated during the combustion process. The method involved continuous measurement of light transmission at two positions in the aft mixing chamber (Fig. 2).

The extinction measurements record the total amount of light removed from a beam passing through the combustion chamber as a result of Mie scattering and absorption by the particulates. The transmission of light through an aerosol of particles is given by Bouguer's Law[11]:

$$T = e^{-\gamma L} \tag{3}$$

The intensity of the light beam decreases exponentially with distance (L) as it penetrates the aerosol, with a rate of decay regulated by the turbidity γ. The turbidity for the case of a polydispersed size distribution is given in Ref. 7:

$$\gamma = \frac{3}{2} \frac{\bar{Q}\, C_m}{D_{32}\, \rho} \tag{4}$$

where C_m is the mass concentration of particles, ρ is the density of an individual particle, D_{32} is the volume to surface mean diameter, and $\bar{Q}$ is the average extinction coefficient. The extinction coefficient $\bar{Q}$ is calculated as a function of particle size distribution, wave length of the light beam and the complex refractive index of the particle using Mie scattering

theory. Values of $\bar{Q}$ have been shown not to be significantly affected when the particles are non-spherical[7].

Using a log normal particle size distribution with a standard deviation of $\sigma = 1.5$ and a refractive index for carbon of 1.95 - 0.66i, Mie extinction coefficients for three wave lengths (4579A, 5145A, & 6328A) can be determined as shown in Fig. 3. Average extinction coefficient curves for a monodispersed size distribution are also shown in Fig. 4. These plots were provided by K. L. Cashdollar of the Pittsburgh Mining and Safety Research Center, Bureau of Mines.

From Bouguer's Law[7] the ratio of the logarithms of the measured transmissions at any two wave lengths is equal to the ratio of the computed average extinction coefficients.

$$\frac{\ln T_{\lambda_1}}{\ln T_{\lambda_2}} = \frac{\bar{Q}_{\lambda_1}}{\bar{Q}_{\lambda_2}} \tag{5}$$

Curves from which average particle size can be found as a function of the $\bar{Q}$ ratios are shown in Figs. 5 and 6.

As noted by Cashdollar[7], use of three wave lengths provides a redundancy over most of the particle size range. If the three measured log transmission ratios do not yield the same approximate average particle diameter, then the particle size distribution and/or the refractive index may not be correct.

Once the mean particle size and extinction coefficient have been determined, the mass concentration can then be computed from:

$$C_m = -\frac{2}{3}\frac{\rho D_{32}}{\bar{Q}_\lambda L} \ln T_\lambda \tag{6}$$

provided that the particle density is known.

As previously mentioned, the use of extinction methods assumes that an accurate knowledge of the refractive index is available. There exists an uncertainty as to the refractive index of carbon soot. Ref. 8 suggests the possibility that the refractive index may vary with the H/C ratio. Senfleben and Benedict[12] have determined refractive index values of 1.95-0.66i and 1.75-0.74i respectively. Cashdollar originally chose to use 1.57-0.56i from from Dalzell's work[13], but later lowered the imaginary part to 0.33i in order to obtain better agreement between three wave lengths[14].

Average particle diameters computed in the present investigation were based on a refractive index of 1.95-0.66i.

Cashdollar chose to use light wavelengths of 4500, 6328 and 10,000 angstroms. However, in applying the technique to flame measurements, light emission in the infrared region of 10,000 angstroms makes this frequency unusable. For the solid fuel ramjet combustion studied in this investigation 5145Å was used rather than 10,000A. However, it offered less in the way of redundancy for the measurement, as it was closer to the other frequencies than desired. For the purpose of particle diameter determination computed from the extinction coefficient ratios, $\bar{Q}_{6328}/\bar{Q}_{4500}$ was considered most accurate because of the larger spread between the wave lengths[6].

The extinction coefficient curves used were computed for both a log normal particle size distribution with a standard deviation $\sigma = 1.5$ and a monodispersed distribution. Wersborg[15] indicates that for small soot particles in flames a narrow size distribution has been observed to be Gaussian. However, he also reports a change to a log normal distribution in the tail of a flame.

Lester and Wittig[8] conclude from Wersborg's results that for the study of nucleation and surface growth in a combustion environment, the monodisperse approximation is reasonable for the calculation of size and concentration.

Average diameters D_{32} were computed in this experiment from both log normal and monodispersed distributions.

III. DESCRIPTION OF APPARATUS

A. RAMJET MOTOR

The solid fuel ramjet motor was that previously used by Mady[1]. The only modifications made to the motor were the installation of an improved ethylene-oxygen igniter system in the head-end assembly and the machining of 9/16 inch diameter ports in the aft mixing chamber. The ports allowed an external light source to penetrate through the aft mixing chamber at two axial locations (Figs. 2 and 7). Fuel grains used were PMM and an all-hydrocarbon fuel supplied by the Naval Weapons Center, China Lake.

When bypass air was utilized, two 0.813 in. diameter dump ports were used which were perpendicular to the motor centerline. They were located 180° apart and just aft of the mixing chamber recirculation zone.

The inlet diameter was 0.50 inches and the fuel grain internal diameters for the PMM and all hydrocarbon fuels were 1.50 and 1.30 inches, respectively.

The exhaust nozzles used were converging with a 0.746 inch throat diameter for the PMM firings and a 1.0 inch throat diameter for the all-hydrocarbon fuel tests.

B. TRANSMISSOMETER APPARATUS

The light source used was a SLM-1200 slide projector which housed a 1200 watt tungsten-halogen lamp (Sylvania BRN-1200). The light was focused through the projector lens system onto a pin hole on one end of a 3" x 5" x 10" blackened aluminum box (Fig. 7). The pin hole produced a nearly point source illumination and was used with a collimating lens in the box to produce a collimated light beam. The collimated light beam was then directed through a 9/16" diameter hole on the opposite end of the collimator box.

The beam was then split with a 50/50 plate beam splitter. The first beam was directed (through a 9/16 OD x 0.049" wall steel tube) to the front portion of the mixing chamber. The second beam was appropriately deflected and directed to the aft end of the mixing chamber just prior to the exhaust nozzle. After both beams penetrated the chamber cavity they were again directed through tubing to two individual light detector units.

The light directing tubes were sealed using synthetic sapphire windows mounted in an O-ring sealed coupling. The coupling was designed for quick removal of the windows for cleaning between engine firings. The windows were located 10 inches from the combustion chamber.

The distance traveled by the light beam through the 9/16" O.D. (0.46" ID) tubing, prior to reaching the light detector, was nominally 24 inches. This limited the angular field of view of the detector to 1.1° in order to eliminate any significant forward light scattering.

Each detector box consisted of two plate beam splitters which created three individual beams of light (Fig. 8). 2" x 2" narrow pass light filters of wave lengths 6328, 5145 and 4500 Angstroms were placed directly in front of three silicon photovoltaic detectors. The detectors provided adequate spectral response between 2000 and 11,500 Angstroms. The output of each photodetector was input to an operational amplifier, providing linearity between light intensity and voltage output. Both front and back detector systems were tested simultaneously for linearity by placing several calibrated neutral density filters in front of the collimator box output. Both systems (front and back) were linear within 3%.

C. DATA ACQUISITION

All transducer outputs for pressure measurements along with a 5 cycle per second timing signal were connected to a Honeywell Model 2106 Visicorder. Photodetector output was recorded on multiple-pen, paper chart recorders.

D. AIR SUPPLY

A Pennsylvania air compressor supplied air at a pressure of 150 psia. When firing the all-hydrocarbon fuel, the air from the compressor was routed through a Polytherm air heater. This provided non-vitiated hot air up to 840°R.

IV. EXPERIMENTAL PROCEDURE

All test firings were performed in the jet engine test cell at the Naval Postgraduate School

When testing PMM fuel grains, multiple firings were made at bypass ratios (primary/bypass) of 100/0, 70/30, 50/50 and 30/70, with a nominal total air mass flow rate of 0.2 lbm/sec. Reduced mass flow rates of 0.1 lbm/sec with no bypass were also tested. Bypass dump diameters of 0.813" and 0.25" were employed.

When using the all hydrocarbon fuel, bypass ratios of 100/0 and 50/50 were used.

Temperature rise efficiencies were calculated for each test. Inlet temperatures were measured and "acutal" combustor total temperature was calculated using measured flow rates and combustion pressure. The NWC PEPCODE program was used to generate the theoretical combustion temperature and required gas properties (gas constant and specific heat ratio) at the experimentally determined air-fuel ratio.

Weighing each fuel grain before and after a firing provided the needed data for determining the average fuel regression rate and fuel mass flow rate. Regression rate calculations based on inside aft diameter variation were also included in the data reduction.

V. RESULTS AND DISCUSSION

Twelve firings of PMM and six firings of the all-hydrocarbon fuel were conducted. Combustion efficiencies and regression rates were computed using the program developed in Ref.1, with appropriate modifications for the all-hydrocarbon fuel. Table I presents a summary of the major computed performance parameters and light measurement data.

A. PMM FUEL

Transmissivity measurements were successful on both front and back light detector systems when firing PMM fuel at 100/0 and 70/30 bypass ratios. When operating at 50/50 or 30/70, however, the light transmission during steady state burning through the front portion of the mixing chamber was below the sensitivity of the recording system. Light transmission was always measurable in the aft end of the mixing chamber when firing PMM fuel grains.

Test firings of PMM with no bypass (100/0) indicated that the regression rate varied within 3% (except for one test) of equation (2):

$$\dot{r} = 0.0043\ P^{.29}\ G^{.38} \tag{2}$$

The results were also within 5% of the results presented by Boaz and Netzer[16]:

$$\dot{r} = 0.00194\ P^{.51}\ G^{.41} \tag{7}$$

With application of bypass air to the PMM tests, the regression rates continued to follow equation (2). This was opposite to the findings of Mady where regression rates did not vary significantly with bypass and no longer followed equation (2).

The computed combustion efficiencies for bypass and no-bypass test configurations showed (in contrast to Mady's experiments) no degradation in performance (see Fig. 9).

The contradictory results prompted an investigation of possible differences in the PMM fuel and/or in test procedures. All air mass flow measurement orifices were recalibrated and found to be accurate. Samples of PMM used in both experiments were accurately measured for possible differences in density and found equal. Information received from the PMM manufacturer (Rohm-Haas) indicated a possible difference in lots of PMM due to the curing process. It was suggested that when curing thick sections of PMM a possible variation in the amount of residual monomer in the solid may occur. Subsequently, a sample of each lot was ignited in atmospheric air with an oxygen-acetylene torch and a significant difference in the surface combustion was apparent. It can be seen in Fig. 10 that the sample used in this experiment appeared to have a considerable fizz layer on the surface, indicating the probable existence of large quantities of monomers leaving in a gaseous state. The sample from the earlier experiments, although showing some surface fizz, produced large gas bubbles well below a relatively smooth surface.

With the assumption that the previously employed fuel came off the surface predominantly as small polymers rather than monomers, a plausible explanation for the higher regression rates in the bypass runs can be made. For a low mass flux of air through the grain, as for 50/50 bypass, a fuel rich condition occurred. A high concentration of fuel polymers reaching the flame would lead to cracking and the production of increased quantities of free carbon. The increased presence of carbon would enhance radiative heat transfer to the fuel surface, increasing the regression rate.

With the high regression rate and resulting fuel rich environment, the temperatures in Mady's experiments must have been low enough and/or the combustion shear zone thin enough that when bypass air was injected into the aft mixing chamber the combustion process was quenched.

In the current experiments, if monomer production predominates, the reactions would be more rapid and complete and less carbon would be produced by cracking type processes below the flame zone. Less radiative heat transfer would result, with correspondingly lower fuel regression rates. The low regression resulted in near stoichiometric air-fuel ratios within the fuel grain with 50/50 bypass. The bypass air would then mix with the hotter combustion products which include only relatively small quantities of unburned fuel. The subsequent reactions apparently occurred without quenching, resulting in high combustion efficiencies.

Light transmission measurements for no-bypass (high G_{air} through grain) showed greater than 70% transmittance at the end of the fuel grain and greater than 79% transmittance at the entrance to the nozzle. This indicates that only small quantities of particulates leave the fuel port. Assuming for simplicity that the gas properties and carbon concentration are uniform at any cross section of the aft mixing chamber, the percentage of unburned carbon can be estimated. It varies linearly with particulate concentration and gas velocity and inversely with the fuel flow rate. This assumption is obviously weak at the aft end of the grain where reverse flow occurs in the recirculation region. The data are presented in Table I. Table II presents the estimated average percentage of unburned carbon for each of the test conditions. Figs. 11, 12, and 13 present typical light transmission data for various bypass ratios.

Without bypass, reducing air flow rate increased the fuel-air ratio slightly as expected from the behavior of the fuel regression rate. However, the fuel-air ratio remained air rich (stoichiometric A/F = 8.33). The combustion efficiency and the percentage of unburned carbon did not vary appreciably.

With bypass ratios up to 50/50 the fuel-air ratio within the fuel port remained air rich. However, for 50/50 conditions the fuel port fuel-air ratio was nearly stoichiometric. In the 50/50 bypass configuration transmittance at the fuel grain exit was less than 5%. This is considered the minimum measurable transmittance level for the present system. This indicated that greater than 30% of the carbon produced was unburned leaving the fuel grain (or rather leaving the fuel grain and trapped in the recirculation zone). Thus, even with near stoichiometric mixture ratios within the fuel port, a considerable amount of unburned carbon is produced. With the higher regression rates obtained in Mady's experiments, excessive amounts of carbon must have been produced. As the percentage bypass air was increased, more carbon was produced within the fuel grain and more passed through the nozzle. Much of the increased carbon content within the fuel grain was apparently burned in the aft mixing chamber. This is also apparent in Figs. 12 and 13; as the fuel continued to burn, the port mixture became less fuel lean and more carbon was produced, yet the percentage of unburned carbon at the exhaust nozzle remained approximately constant. The combustion efficiency did not change appreciably although a slight increase is noted with increasing bypass ratio to the 50/50 conditions. The high bypass condition (30/70) was the only test conducted in which the fuel-air ratio within the fuel port was fuel rich and it provided the highest combustion efficiency.

For the combustion of PMM with air, 1% unburned carbon would reduce combustion efficiency by approximately 1% (if fuel lean and have chemical equilibrium).

The results presented in Tables I & II indicate that small amounts of unburned carbon in itself is not the cause for low combustion efficiency.

Rather, it appears in this case that unburned gaseous hydrocarbons have the primary affect on combustion efficiency. Port fuel-air ratios close to stoichiometric (or slightly fuel rich) produce thicker boundary layers (higher fuel regression rates relative to air flow rates). This is turn results in a thicker fuel shear layer entering the aft mixing chamber with more unburned hydrocarbons at a higher temperature. When these hydrocarbons are small (monomers, etc.) they apparently burn quite efficiently with the bypass air (or for that matter without bypass air). If the fuel leaving the surface is in larger polymers (as for the fuel-rich bypass conditions in Mady's experiments) more carbon is produced and apparently the aft mixing process becomes much more critical. The temperatures of the larger polymers and the carbon become important and how the bypass air is mixed becomes the dominant variable affecting combustion efficiency.

These results indicate that a fuel which could produce both high regression rates and gaseous monomers would provide a high performing solid fuel ramjet without the complexity of bypass.

The percentage of unburned carbon is determined from the computed carbon concentration, C_m, which in turn is determined by the transmissometer readings. The calculated particle sizes were in the 0.1 to 0.25 μm range. This agrees with carbon particle size measurements in flames and smoke made by other investigators. In any case, a variation in particle diameter between 0.1 and 0.3 μm does not significantly affect C_m since in this range $\bar{Q}$ varies in an approximately linear manner with particle diameter, D_{32}. This can be seen from the equation for particle mass concentration:

$$C_m = \ln T \left(- \frac{2}{3} \frac{\rho D_{32}}{\bar{Q} L}\right) .$$

One of the more interesting results of these experiments was the unexpected change in bypass performance compared to the earlier data for PMM[1]. The production of monomers enhanced bypass combustion efficiency but reduced regression rate by significantly reducing the radiation produced by carbon particles. These differences apparently resulted from small variations in manufacturing methods. These observations indicate that the often observed run-to-run variations in combustion efficiency may be due in part to small variations in the fuel curing process.

B. ALL-HYDROCARBON FUEL

Transmissivity measurements for the all-hydrocarbon fuel firings were less than 5% at both positions in the mixing chamber, when no-bypass was employed. However, during a 50/50 bypass run a 9% transmittance was measured at the fuel grain exit and 33% transmittance at the nozzle entrance. For the all-hydrocarbon fuel this corresponded to 18% and 10% unburned carbon, respectively. Both runs achieved nearly the same combustion efficiency. The stoichiometric air-fuel ratio for this fuel was approximately 13. The fuel port fuel-air ratios were quite fuel rich. For this fuel, 2% unburned carbon changes temperature rise efficiency by approximately 1% (increases for fuel rich and decreases for fuel lean).

The question then is: why, in the no-bypass run could light not be measured at the grain exit, and yet in the 50/50 test (a more fuel-rich condition at the grain exit) light was measured? Typically, a higher percentage of unburned fuel is produced in bypass tests. One plausible cause could be the effect of high air velocity (and temperature) during the non-bypass run. The polystyrene in the fuel could have been stripped from the surface and passed into the aft mixing chamber.

The two runs conducted were not for the same total flow rate. However, the bypass did not affect the combustion efficiency. Other investigators have reported increases and decreases in combustion efficiency with varying bypass configurations and dump momentum. Too little data for the all-hydrocarbon fuel were obtained in this study to reach any new conclusions with regard to the effect of bypass on combustion efficiency.

VI. CONCLUSIONS AND RECOMMENDATIONS

1) The light extinction measurement provides a valuable new tool for the study of combustion within the solid fuel ramjet.

2) The optical technique has some limitations, the major ones being: a) the maximum amount of carbon particles measureable is limited to the sensitivity in the low transmission levels; b) larger particles/material flowing in a system can prevent light measurements; and c) predicted particle size is somewhat sensitive to the type of particle distribution and refractive index assumed.

3) The percentage of unburned carbon does not correlate with combustion efficiency.

4) Variations in fuel manufacturing processes apparently can significantly change the combustion behavior.

5) High air flow rate can apparently strip polystyrene from all-hydrocarbon fuel.

6) Fuels should be developed which can yield both high regression rates and monomer decomposition.

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Table I. Summary of Experimental Results

	PMM												ALL HYDROCARBON	
% BYPASS	100%/0%					70%/30%	50%/50%					30%/70%	100%/0%	50%/50%
	1	2	3	4	5	6	7	8	9*	10	11	12	13	14
P_c (psia)	54.6	35.6	39.0	54.4	55.9	48.0	58.9	47.4	47.4	47.4	48.8	46.6	49.6	62.1
$\dot{r} \times 10^3$ (in/sec)	5.89	4.26	4.24	5.87	6.23	4.67	5.03	4.20	4.10	4.17	4.30	2.95	17.1	14.0
$\dot{w}_{Primary}$ (lbm/sec)	.203	.123	.145	.199	.203	.14	.128	.107	.102	.106	.100	.07	.297	.20
$\dot{w}_{Bypass}$ (lbm/sec)	0	0	0	0	0	.06	.131	.100	.103	.103	.101	.13	0	.18
A/F	12.2	10.6	12.4	13.0	11.7	15.6	18.8	18.2	18.3	18.5	17	20.4	8.89	14.1
$(A/F)_{Fuel\ port}$	12.2	10.6	12.4	13.0	11.7	10.9	9.4	9.11	9.15	9.25	8.5	6.12	8.89	7.05
$\eta_{\Delta T}$	.90	.89	.94	.91	.90	.88	.92	.90	.95	.90	.98	.99	.89	.87
$^{**}T_{Front}$ (6328)	.57	.78	.70	.74	.71	.46	0	0	0	0	0	0	0	.09
$^{**}T_{Back}$ (6328)	.94	.87	.97	.79	.84	.71	.65	.66	.59	-	.56	.68	0	.33
$^{***}D_{32_{Front}}$ (μm)	.20	.18	.15	.2	.17	.15	-	-	-	-	-	-	-	.125
$^{***}D_{32_{Back}}$ (μm)	.14	.45	-	.17	-	.27	.265	.22	.23	-	.30	.17	-	.10
$C_{m_{Front}}$ (gm/cm^3)	1.67×10^{-6}	7.48×10^{-7}	1.14×10^{-6}	8.9×10^{-7}	1.04×10^{-6}	2.49×10^{-6}	-	-	-	Light Source Failure'	-	-	-	8.05×10^{-6}
$C_{m_{Back}}$ (gm/cm^3)	2.76×10^{-7}	5.99×10^{-7}	-	7.15×10^{-7}	-	1.04×10^{-6}	1.27×10^{-6}	1.22×10^{-6}	1.56×10^{-6}		1.86×10^{-6}	1.45×10^{-6}	-	4.2×10^{-6}
% unburned carbon														
FRONT	4.7	3.2	4.9	2.5	2.80	8.5	-	-	-		-	-	-	18.8
BACK	0.7	2.6	-	2.0	-	3.5	3.9	4.5	6		7.0	6.2	-	10.0

*High bypass dump momentum

** Transmittance at t_{ign} + 16 sec for PMM fuel. Total burn time for PMM ≈ 40 sec, for all H/C ≈ 15 sec.

*** Calculated from 6328/4500 for σ = 1.5

Table II. Estimated Average Percentage of Unburned Carbon

FUEL	ESTIMATED % UNBURNED CARBON		% AIR (FUEL PORT/ BYPASS)	$\bar{\eta}$
PMM	3.3	1.4	100/0	0.90
	4.0	2.6	50/0	0.91
	8.5	3.5	70/30	0.88
	>30	5.3	50/50	0.94
	>30	6.2	30/70	0.99
ALL HC	–	–	100/0	0.89
	18	10	50/50	0.87

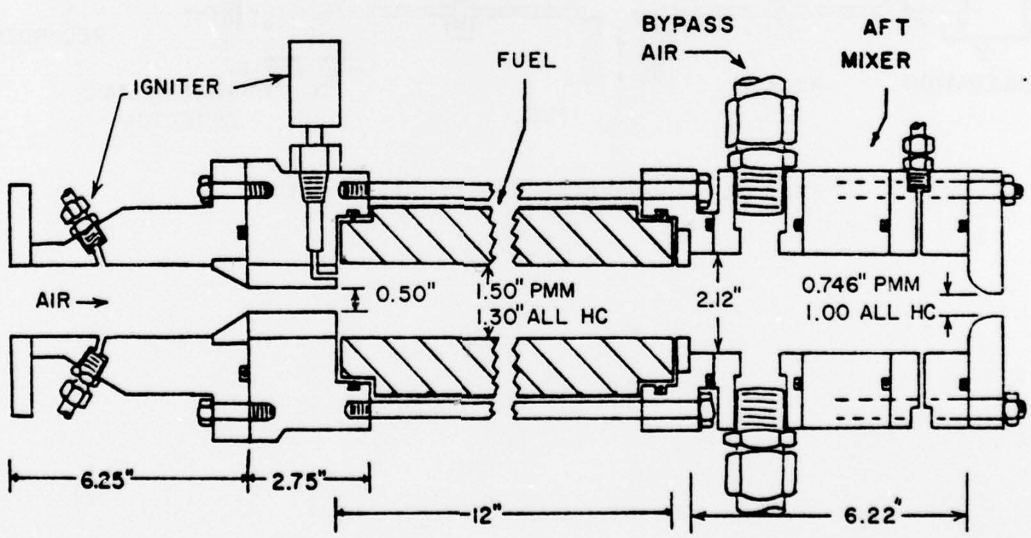

Fig. 1. Schematic of Solid Fuel Ramjet

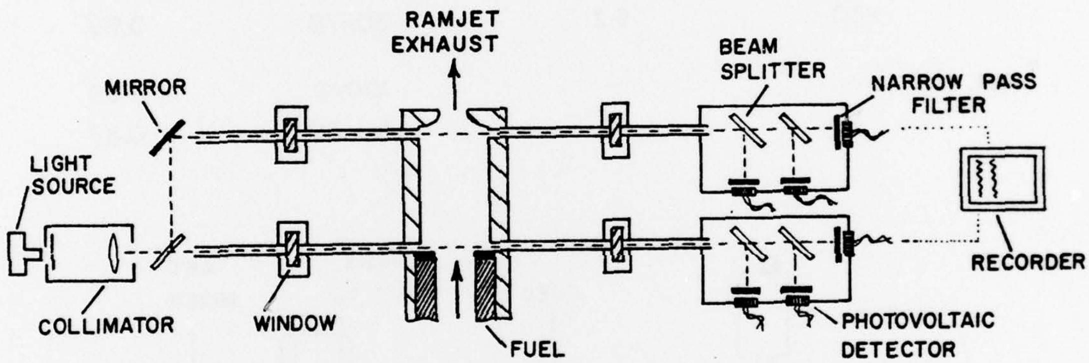

Fig. 2. Schematic of Optical Detector

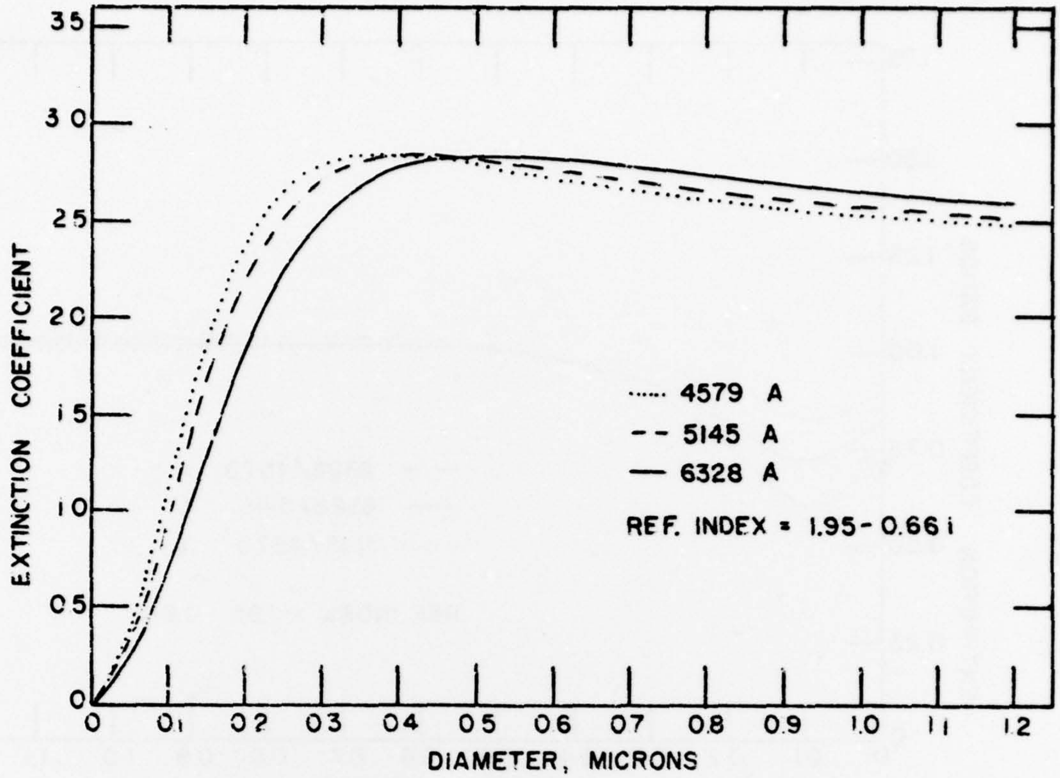

Fig. 3. Mie Extinction Coefficients, Log Normal (σ = 1.5) (Cashdollar)

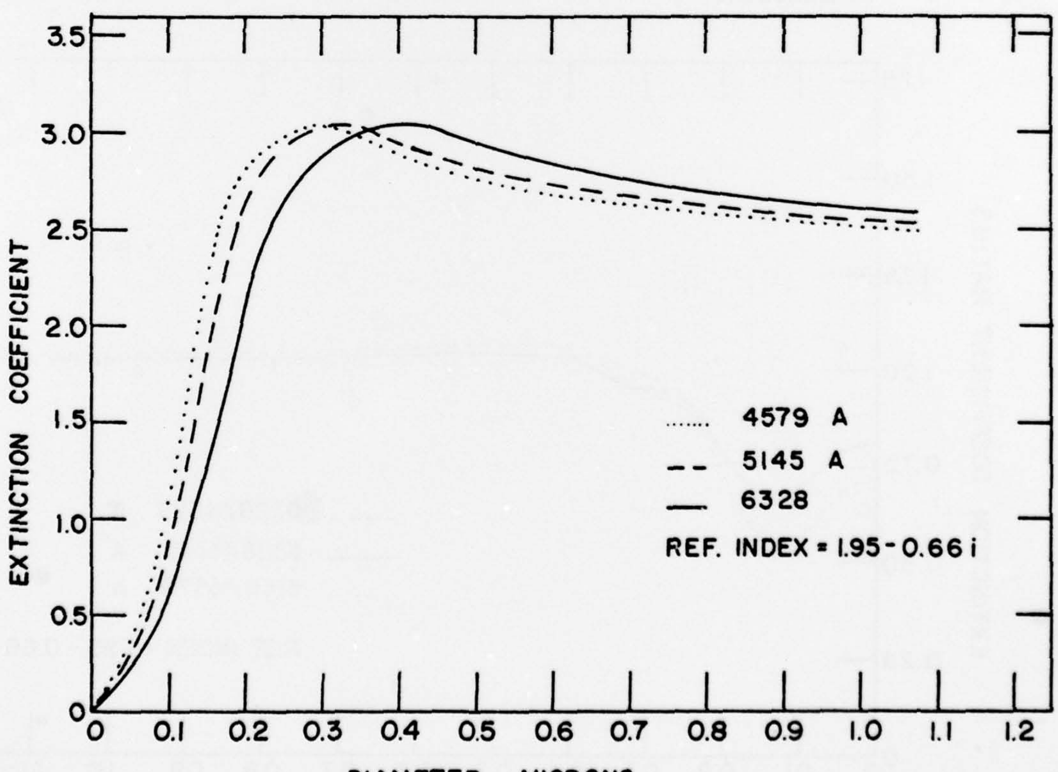

Fig. 4. Mie Extinction Coefficients, Monodispersed (Cashdollar)

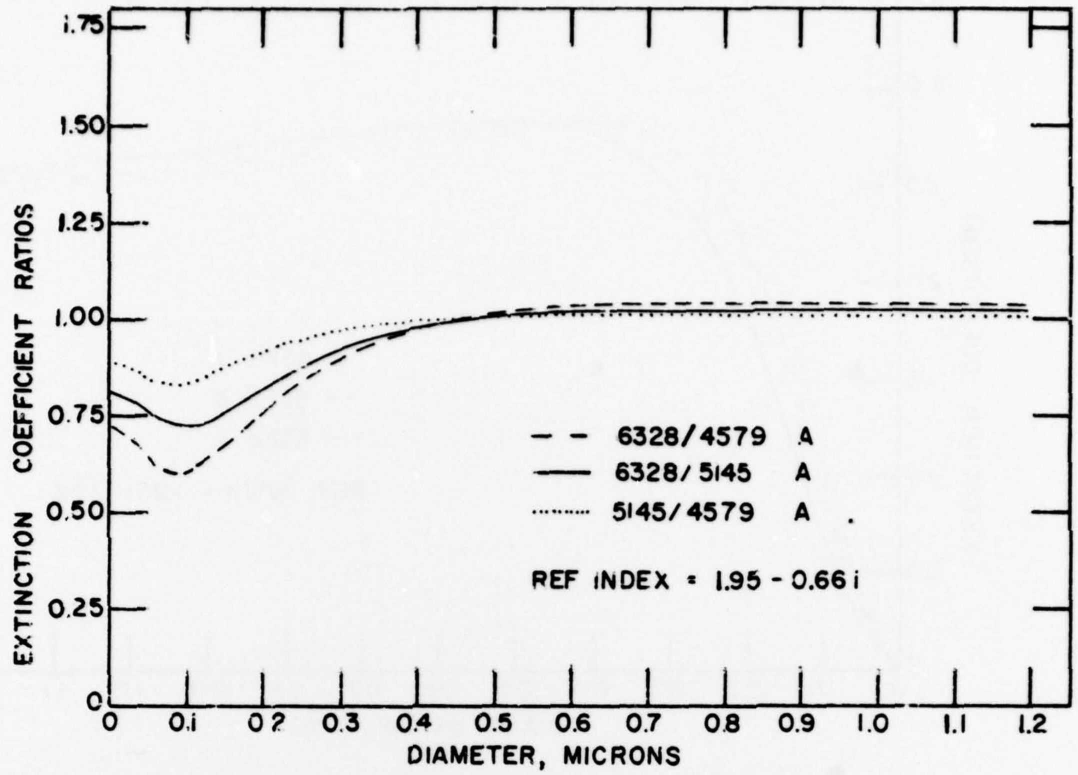

Fig. 5. Average Extinction Coefficient Ratios, Log Normal (σ = 1.5) (Cashdollar)

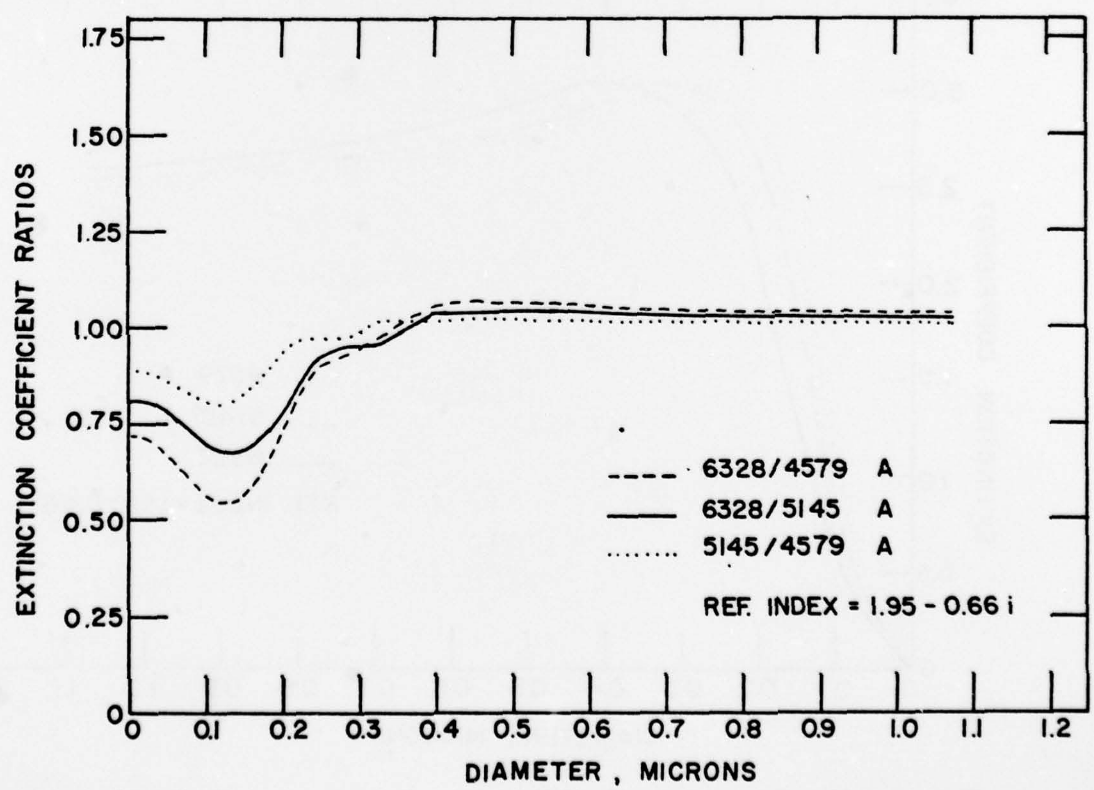

Fig. 6. Average Extinction Coefficient Ratios, Monodispersed (Cashdollar)

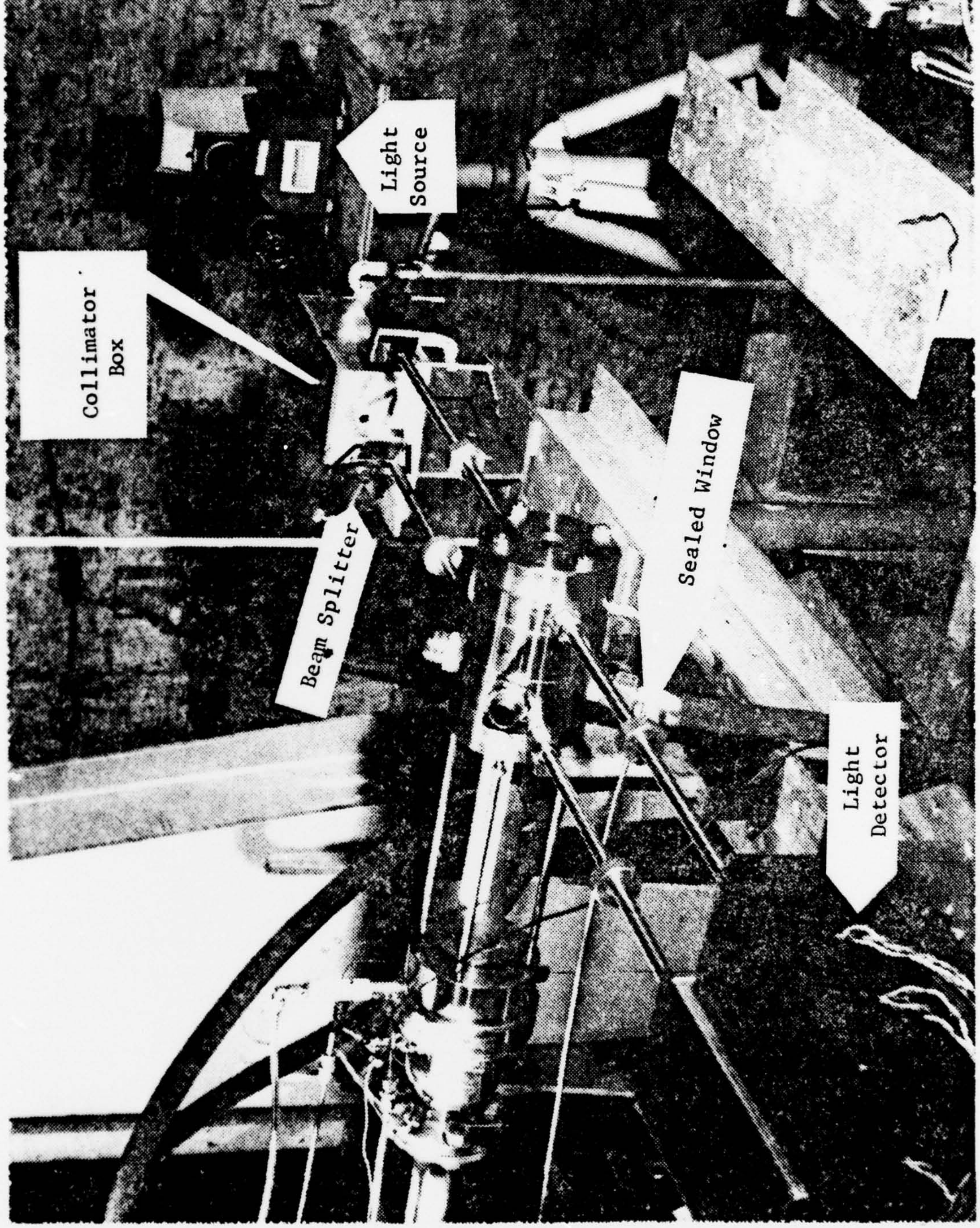

Fig. 7. Photograph of Transmissometer Apparatus

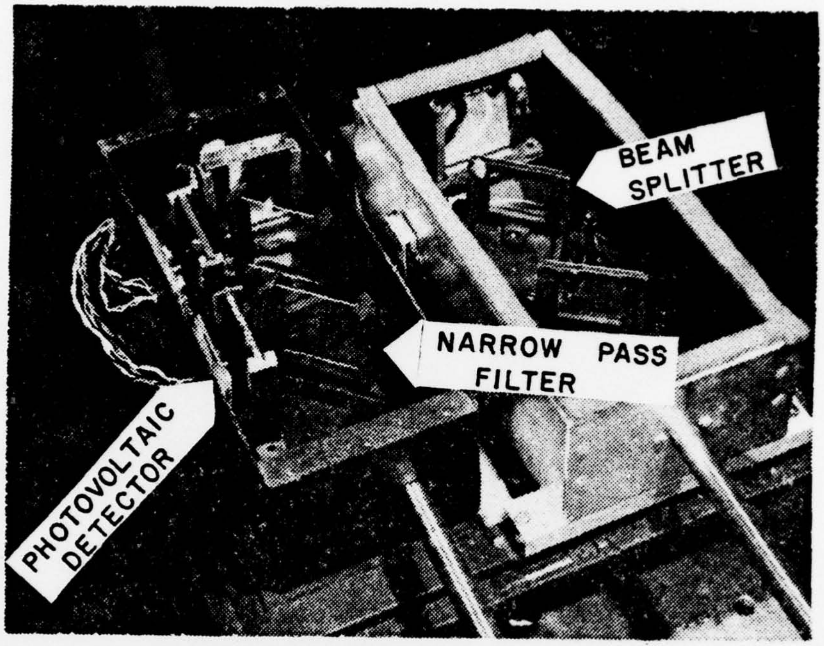

Fig. 8. Photograph of Light Detector Apparatus

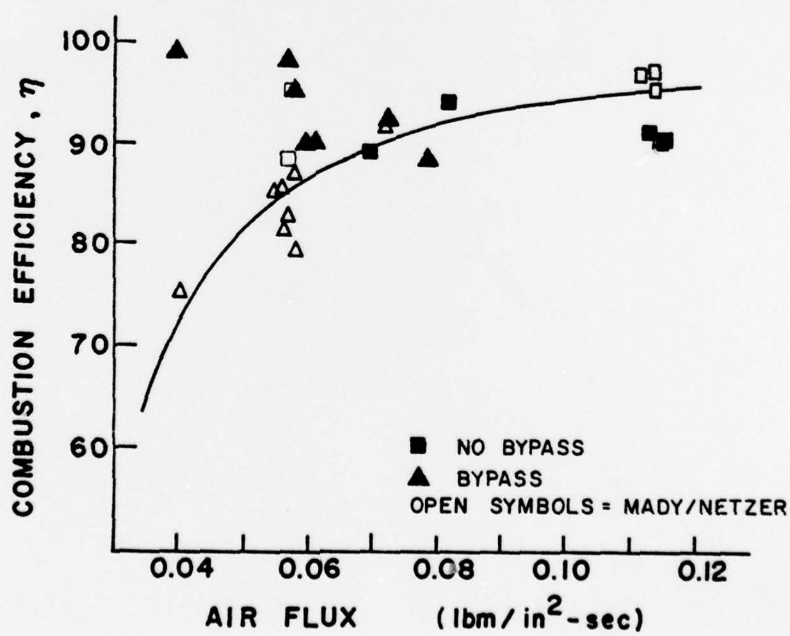

Fig. 9. Combustion Efficiency vs. Air Flux for PMM Fuel

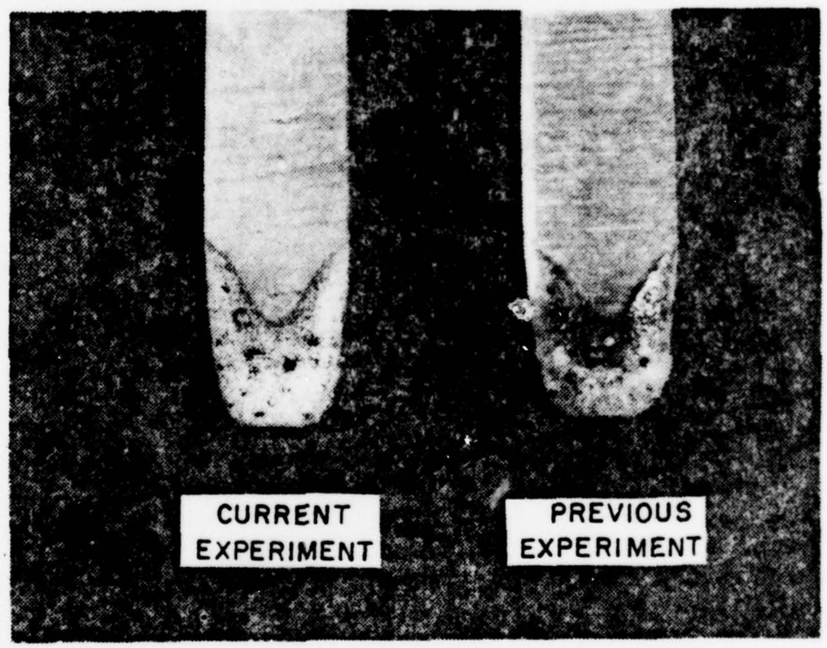

Fig. 10. Photograph of PMM Samples Burned at Atmospheric Conditions

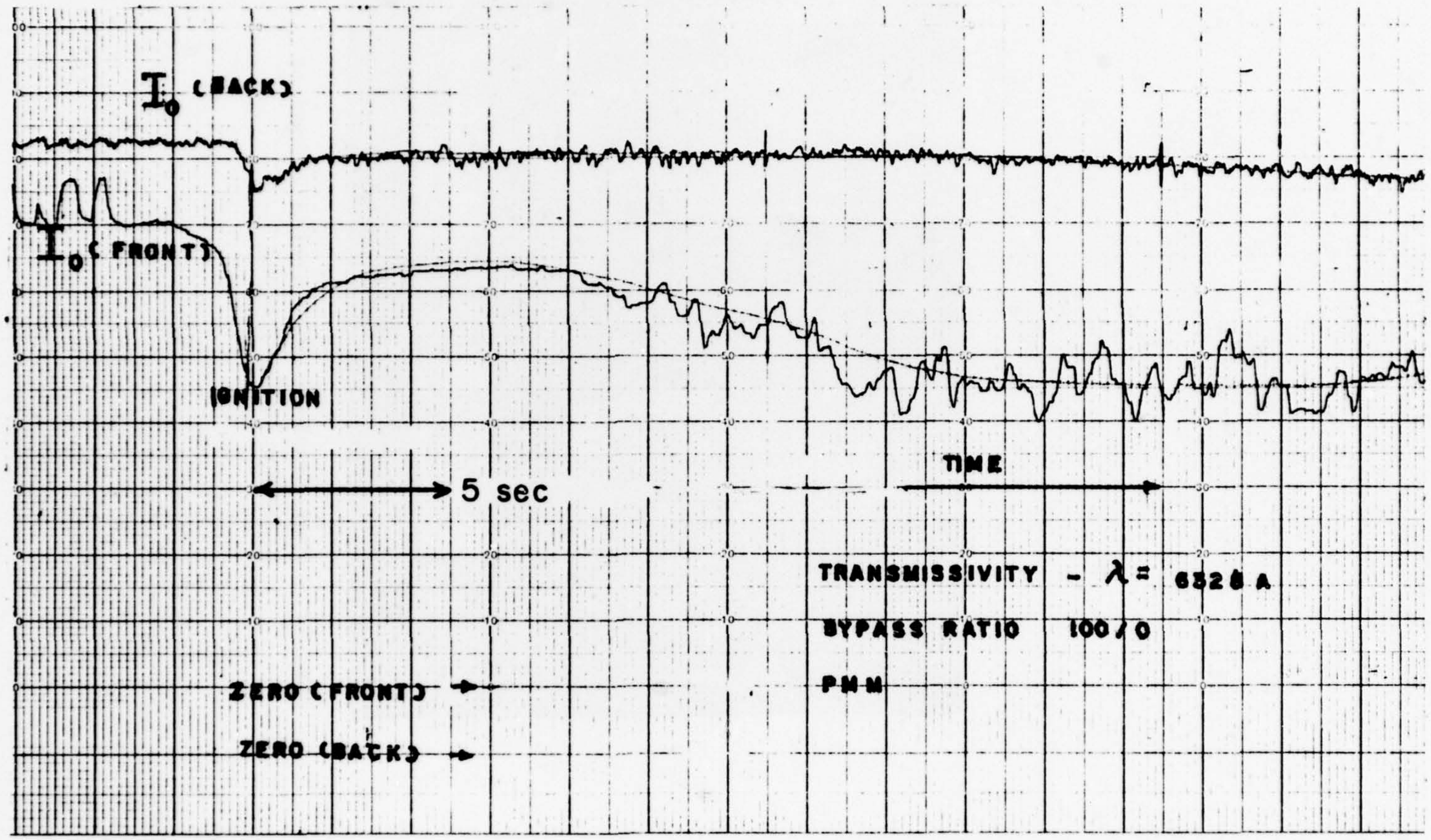

Fig. 11. Light Transmission Data for PMM Fuel with 100/0 Bypass Conditions

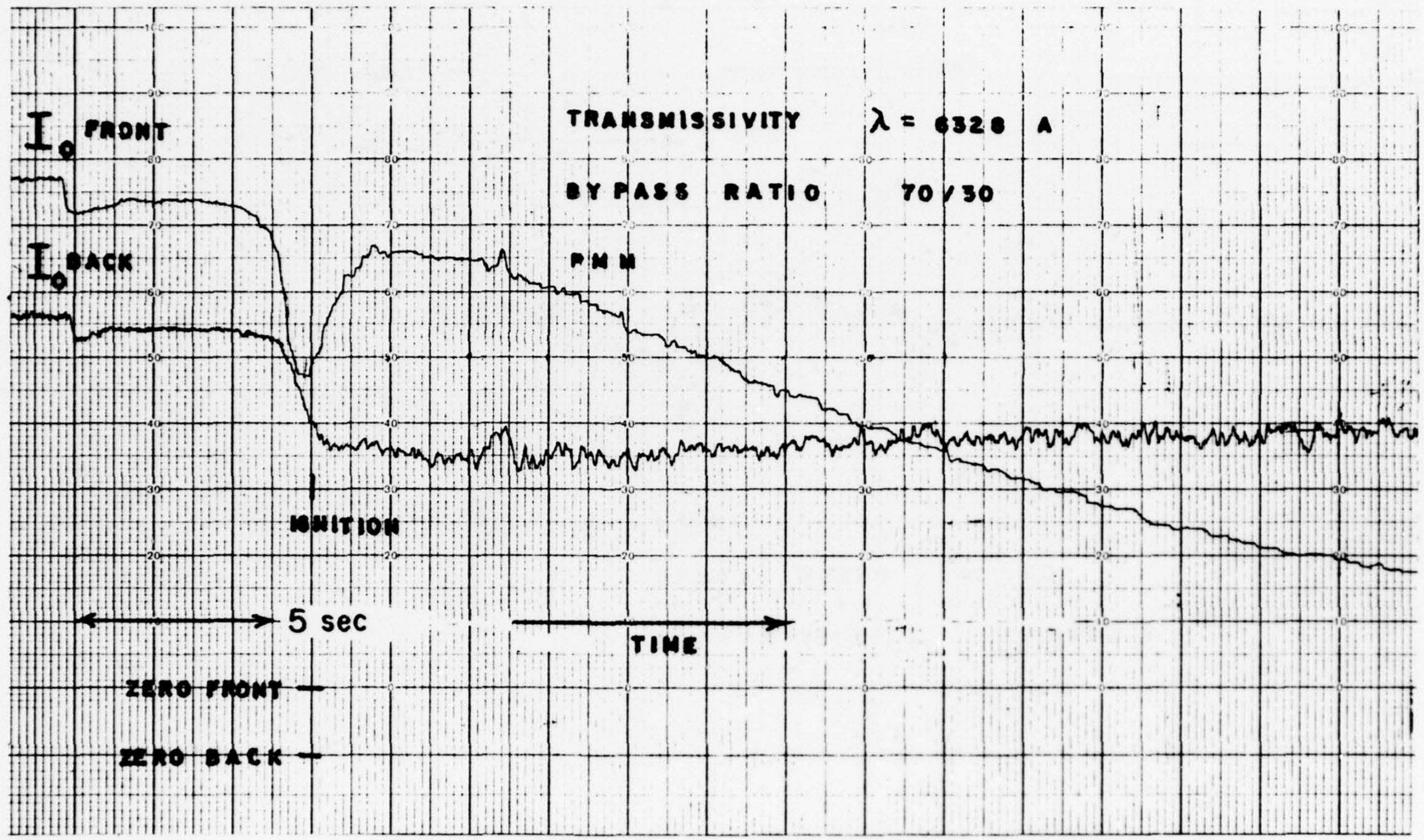

Fig. 12. Light Transmission Data for PMM Fuel with 70/30 Bypass Conditions

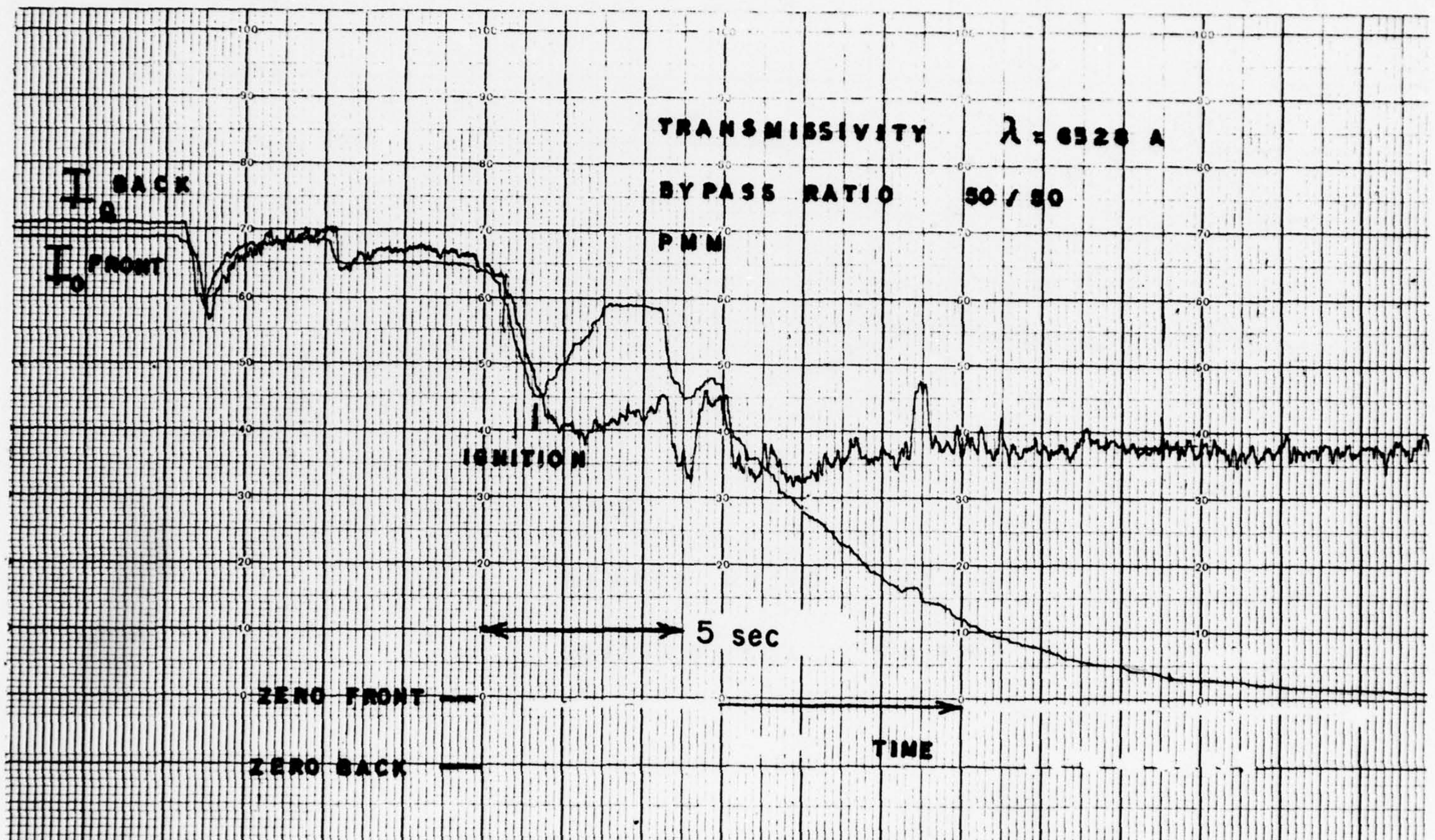

Fig. 13. Light Transmission Data for PMM Fuel With 50/50 Bypass Conditions

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